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Particle-reinforced composites

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Intended Learning Outcomes

At the end of this section, students will be able to:-

- Understand what composites are and how they are classified.

- Reason why composites are used in place of other material types.

At the end of this lecture summary students will be able to identify composite materials, their classification and the reasons for their development and use.

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Composites

concrete | Carbon fibres | fibreglass

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•The advent of composites as a distinct class of (man made) materials can be traced back to the mid 20th century, with fibre reinforced plastics.

•But as will be discussed these composites were not the earliest used by mankind.

•One composite that has had a profound effect on our quality life is concrete. This cheap structural engineering material has been increasingly employed since the 1960's , making housing affordable and within reach of most. It is also the major structural component of large scale engineering constructions, for example, motorway bridges.

•In contrast carbon fibre composites are not cheap (although there is always a drive to reduce costs).

•The advent of carbon fibres has been driven by high performance demands. The example shown here is a high performance race car, where there is extensive use of composites in the chase to reduce weight, without compromise on strength.

•In this lecture summary we will explore the different types of composites and why they are used and the relationship between their structure and performance.

Airbus A380

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Composites make up more than 20% of the A380's airframe.

By Jun Acullador, released under CC BY-NC 2.0 license
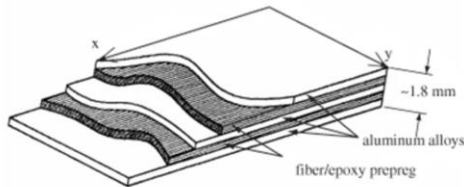
Figure 1. Configuration of continuous fiber/metal/epoxy hybrid composite (3/2 lay up).

~1.8 mm
aluminum alloys
fiber/epoxy prepreg

GLARE (GLAss-REinforced fibre metal laminate).

Light weight outer box design
CFRP upper deck floor berns
Fin box, rudder HTP box and elevators in monolithic CFRP
Upper fuselage panels in GLARE
CFRP pressure bulkhead
Advanced aluminium alloys for inner and mid-wing covers
CFRP centre wing box
Welded stringers on lower fuselage panels
SPF-DB/titanium in pylon
Thermoplastic fixed wing leading edge

Figure 2. Metal/fiber applications in A380 airplane from Airbus[15].
Mat. Res. vol.9 no.3 2006

•The wide variety of different composites and their applications are illustrated in this slide, showing the use of composites in the Airbus 380.

•Throughout the body of the 380 composites are employed.

•The different combination of materials include glass fibre reinforced composites, carbon fibre reinforced composites and fibre reinforced metal composites. These composites have progressively replaced the more traditional engineering materials, metals, metal alloys etc.

•The slide also illustrates that it is not just the application of composites but also their lay up that provides enhanced performance (rhs).

Composites

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Composites: Composed of two (or more) individual materials from the categories of metals, ceramics and polymers.

| Material class	Tensile Strength	Elastic Modulus	Ductility	Toughness	Density
Metals	Good	Good	OK	Good	Poor
Polymers	Poor	Poor	Good	Poor	Good
Ceramics	Good	Good	Poor	Poor	OK

COMPOSITES

A composite is considered to be any multiphase material that exhibits a significant proportion of the properties of both constituent phases such that a better combination of properties is realized.

• Composites are comprised of two or more materials such as glass fibres in a polymer matrix.

• They are seen as multiphasic materials where in combination a superior performance is realised.

• Composites combine low density with high strength.

Natural composites

Wood: A natural composite of cellulose fibres (which are strong in tension) embedded in a matrix of lignin which resists compression.
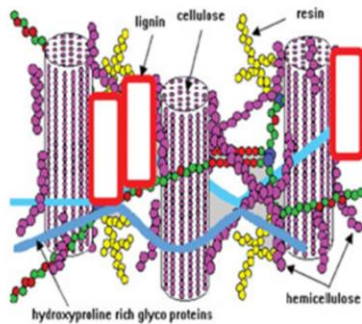
Wood Microscopic Structure

• The engineering/structural advantages of combining dissimilar materials is not a man made discovery.

• Over billions of years nature has built her own composites. A great example is wood. Cellulose fibre reinforcement of a lignin matrix provides a strong, structural material that can resist large compressions.

• A feature to note here, that we will return to, is the direction of fibre reinforcement.

• That is the cellulose fibres are not orientated randomly, but are aligned to provide optimal tensile strength in the direction it's required.

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Composites

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The simplest composite materials are composed of just two
phases; the matrix, which is continuous and surrounds the
other phase, often called the dispersed phase.

Adapted from Fig. 16.1(a), *Callister & Rethwisch 8e.*

•The simplest composite materials are composed of just two phases.

•The first is termed the matrix, which is continuous and surrounds the
other phase which is often called the dispersed phase.

•In the schematic shown we see that in (a) there is a change in the
concentration of the dispersed (fibre) material.

•In (b) the size of the dispersed phase, (c) shape, (d) the distribution,
and in (e) the orientation.

•All these will effect the final performance of the composite.

Terminology and classification

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Composites: Multiphase material with significant presence of each phase.

Dispersed Phase: Enhances matrix properties. May increase E, σ_y, TS or creep resistance.

Matrix: The continuous phase. Fills volume, provides shape. Transfers stress to other phase(s) and protect phases from the environment.
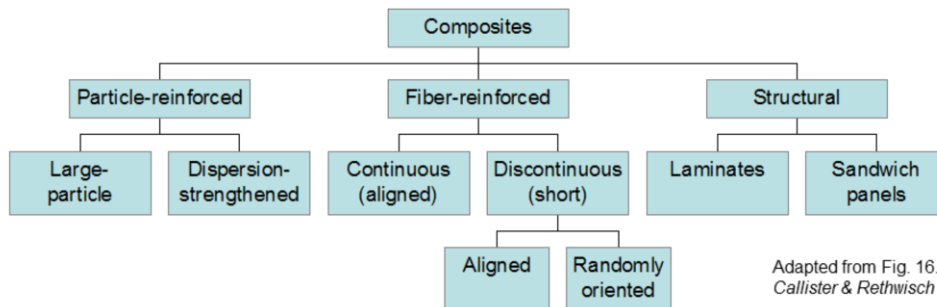
Classification:

MMC, CMC, PMC

metal   ceramic   polymer
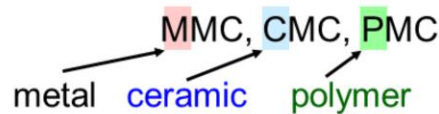
•To obtain a significant contribution from each phase to the overall property of the composite there is the requirement that there needs to be a significant presence of each phase.

•This is usually described in terms of the volume fraction of each phase; a point we will return to later.

•The dispersed phase is added to enhance the properties of the matrix material. These properties are usually mechanical properties such as Young's modulus, tensile strength, etc.

•The matrix phase is continuous. This phase fills volume, provides shape and also protects the dispersed phase. It is important that there is a transfer of stress from the matrix to the dispersed phase and the matrix is usually a fairly ductile material.

•The three classes of composite then are the metal, ceramic and polymer matrix composites.

Composite classification

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                        ┌─────────────┐
                        │ Composites  │
                        └─────────────┘
          ┌──────────────────┼──────────────────┐
┌──────────────────┐ ┌──────────────────┐ ┌──────────────┐
│ Particle-reinforced│ │ Fiber-reinforced │ │  Structural  │
└──────────────────┘ └──────────────────┘ └──────────────┘
   ┌──────┴──────┐      ┌──────┴──────┐      ┌──────┴──────┐
┌────────┐ ┌────────────┐ ┌──────────┐ ┌────────────┐ ┌──────────┐ ┌──────────┐
│ Large- │ │ Dispersion-│ │Continuous│ │Discontinuous│ │Laminates │ │ Sandwich │
│particle│ │strengthened│ │(aligned) │ │  (short)   │ │          │ │  panels  │
└────────┘ └────────────┘ └──────────┘ └────────────┘ └──────────┘ └──────────┘
                                    ┌──────┴──────┐
                              ┌─────────┐ ┌──────────┐
                              │ Aligned │ │ Randomly │
                              │         │ │ oriented │
                              └─────────┘ └──────────┘
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Adapted from Fig. 16.2,
Callister & Rethwisch 8e.

•There are 3 main divisions of composites; particle- and fibre-reinforced and structural.

•Within each of these divisions there are sub-divisions and each have an influence on the composite performance, processing and cost as we will see later.

•Points to further note are the following; In particle reinforcement, the particles are generally equiaxial; that is approx the same in all directions, but for fibre reinforcement there is a large difference in fibre length to fibre diameter, where l>> d.

•This has profound effects on the overall composite property, particularly the load bearing properties of the final composite.

Particle composites

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Particle-reinforced   Fiber-reinforced   Structural

Large-particle composites: particle-matrix interactions cannot be treated on the atomic or molecular level.

The particulate phase is harder and stiffer than the matrix.

Cheap fillers: reduces cost (as the particles are much less expensive than the matrix).

Resist localised deformations: Particles tend to restrain movement of the matrix phase in the vicinity of each particle.

•The first example of particle composites are the large particle composites. These are known as such because the interactions between the matrix phase and particle phase cannot be examined on a molecular, atomic level.

•Here the particle phase is generally tougher than the matrix and, in addition to acting as a cheap filler material, tend to resist localised deformations.

•Portland cement is an example of a large particle reinforced composite.

Particle composites

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Particle-reinforced   Fiber-reinforced   Structural

Dispersion-strengthened composites:

Particles smaller: diameters between 10 and 100 nm.

Yield and tensile strengths, hardness are improved.

The small dispersed particles hinder or impede the motion of dislocations (plastic deformation).

•Dispersion strengthened composites have much smaller particle sizes whose interactions with the matrix can be seen at the molecular level.

•These particle-matrix interactions at the molecular level increase the overall strength of the composite.

•The small particles also resist dislocation motion throughout the composite in a similar manner to the pinning of precipitate hardened metals.

Particle composites

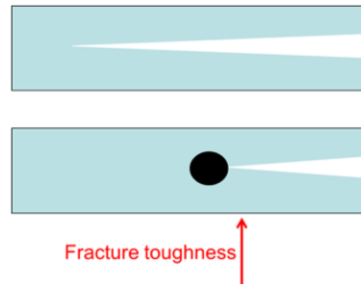Particle-reinforced   Fiber-reinforced   Structural

1. **Large-particle**:
Particles should be evenly distributed throughout the matrix.

Mechanical properties are enhanced with increasing particulate content.

2. **Dispersion strengthened**:
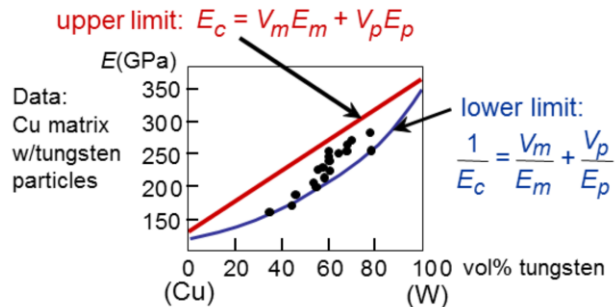Matrix supports load, small particles stop crack propagation

Fracture toughness

•Returning to large-particle reinforcement the key points are that the particles should be evenly distributed throughout the matrix.

•The composite's mechanical properties are increased with increasing particulate content; increasing this increases the interfacial area between the particulate and the matrix.

•For dispersed strengthened composites, the matrix supports the load whilst small particles act to stop crack propagation through the matrix material.

•We can see examples of particulate composites with all three material types (metals, polymers and ceramics).

Particle composites

Two 'rule of mixture' extremes:

Elastic modulus, E_c:

upper limit: $E_c = V_m E_m + V_p E_p$

Data:
Cu matrix
w/tungsten
particles

lower limit:

$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_p}{E_p}$$

Adapted from Fig. 16.3,
Callister & Rethwisch 8e.
(Fig. 16.3 is from R.H.
Krock, ASTM Proc, Vol.
63, 1963.)

Application to other properties:

Electrical conductivity, σ_e: Replace E's in equations with σ_e's.
Thermal conductivity, k: Replace E's in equations with k's.

•The properties of the composite reinforced with large particle filler can be predicted using 2 rule of mixture equations.

•Let's consider using for example the elastic modulus.

•The anticipated upper and lower values for E can be obtained from two fairly simple equations.

•The upper value is given by E subscript c, the elastic modulus of the composite equals the product of the matrix volume and elastic modulus plus the product of the particle volume and elastic modulus. We can see from this equation that the greater the volume fraction of particle the greater E subscript c.

•The lower limit of E subscript c is given by a similar, proportional equation here in blue. Interestingly this equation is expressed in reciprocal terms.

•Again the overall effect of a greater volume of particle is to produce a stiffer composite.

•When experimental data for a Cu matrix reinforced with tungsten particles is plotted as seen here we see excellent agreement with the theory as the values all fall between the two limits.
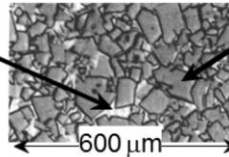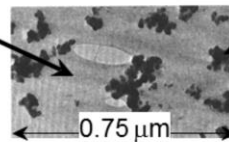
•We find large particle composites with all 3 major classes of materials (metals, ceramics and polymers).

•Cermets are ceramic reinforced metal matrices. In the example shown at the top of the slide, hard particles of ceramic carbide (WC, or TiC) reinforce a ductile metal matrix (Co).

•Cermets are extensively used in cutting tools. The Carbide particles provide the cutting surface, but the carbides are brittle and the required toughness is provided by the metal matrix. It also dissipates heat during cutting.

•A further example at the bottom of the slide is the use of carbon particles (carbon black) to enhance the strength and toughness, tear and abrasion resistance of rubber (the matrix material).

•In these two examples the relative sizes of the particle phase is quite different. Almost three orders of magnitude. The much larger carbide particles provide a cutting surface. But in the case of the carbon filler, the dispersed phase acts to impeded crack propagation.
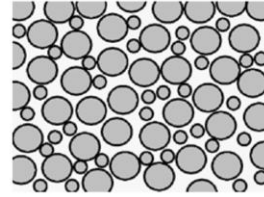
Particle composites

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Concrete - gravel + sand + cement + water
Sand fills voids between gravel particles.

Reinforced concrete - Reinforce with steel rebar or remesh - increases strength - even if cement matrix is cracked.

From ciks.cbt.nist.gov

Pre-stressed concrete - Rebar/remesh placed under tension during setting of concrete. Release of tension after setting places concrete in a state of compression. To fracture concrete, applied tensile stress must exceed this compressive stress.

Post-tensioning – tighten nuts to place concrete under compression

threaded rod

nut

- •A further example that we started this lecture summary with is concrete.
- •Here the matrix material cement is reinforced by two particle fillers; gravel and sand.
- •These 2 fillers are very different in size. The much smaller sand particles fill voids between the larger gravel particles.
- •For effective reinforcement it is important that the cement thoroughly wets the 2 particle fillers. This is why the proportion of cement to water is important.
- •However even with these 2 particle reinforces, cement (concrete) is still relatively weak and brittle.
- •Whilst the compressive strength of concrete is good, the tensile strength is poor.
- •For this reason it has become common practice to further reinforce with steel bars (rebar) or mesh. This increases strength, particularly when the concrete begins to crack.
- •Another approach to enhancing the tensile strength of concrete is to put the steel into tension as the concrete sets around the steel.

Summary

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- Composites are classified according to both the matrix material and reinforcement structure.

- Composites enhance mechanical properties such as Young's modulus and stress.

•So in summary composites are classified by both the matrix materials and structure.

•Generally the filler material enhances the mechanical properties of the matrix material.

Thank you

If you have any questions or desire further clarification please post a question or comment on the Engineering Materials Discussion Forum.